PHENOLIC RESINS FOR PLYWOOD

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INTRODUCTION

During the last decade, one of the outstanding developments in the resin field, which witnessed many important advances during this period, was the growth of resin-bonded plywood. (1,2,14,15,16,26). This development, because it took place in somewhat unspectacular fashion, has not perhaps been appreciated by those not directly interested in plywood. Moreover, resin-bonded plywood is not readily identifiable as such and there are many applications where it is employed without the fabricator or ultimate user being aware of its identify. There are in the United States today approximately 150 hot presses. If this figure is compared with less than a dozen in the year 1934, some idea of the rapid growth during the last five or six years may be obtained. Compared to the total of approximately 7,000 hot presses in the molding industry, it is true that the figure of 150 is not particularly impressive. However, the capacity of a plywood hot press is generally very high. Practically all of them are multiple opening; they may have as many as twelve platens; and they range in size up to 100"x150". This permits a productive capacity measured in many thousands of square feet per day for a single press. Unfortunately, it is not possible to obtain an accurate figure on the total volume of resin-bonded plywood, but it runs to many million square feet per month. The actual total of resin used in the manufacture of plywood is not accurately known, but it is estimated to be between five and ten million pounds per year, a figure that is relatively small compared to the use of phenolic resins in such fields as molding powders, laminating varnishes, and oleo-resinous varnishes. However, again it must be pointed out that in the manufacture of plywood, the phenolic resin is a relatively small proportion of the total weight, being generally less than 10%.

In this paper, we will, first of all, review the growth of phenolic resin bonding from the beginning of the century to the present time. We propose to divide this development into two parts; first, from 1901 to 1934, and second, from 1934 to the present. The year 1934 is chosen advisedly as the division point because this marks the year when Tego Resin Film was first manufactured in the United States. From that point on the growth of resin bonding proceeded rapidly.

It might be well here to say something about the nature of the resins which will be covered. In referring to phenolic resins, we mean not only resins manufactured from phenol itself, but also products made from cresols, xylenols, and other substituted phenols. For all practical purposes, however, the resins used commercially are prepared almost exclusively by reacting formaldehyde with phenol or commercial cresylic acid. No attempt will be made to cover the chemical reactions involved in the preparation of the resins nor their behavior during the process of hot pressing. These are very similar to those involved in the manufacture and curing of the thermosetting phenolic resins used in molding and are fully described elsewhere. (10,20)

Perhaps not out of place here is a word concerning the nature of the adhesive forces acting between resin and wood. There are two general theories. One postulates that the action is entirely mechanical and that the resin is imbedded in the pores of the wood, the strength of the bond depending in part on the degree of penetration and the cohesive strength of the cured resin. The second or "polar" theory emphasizes the influence of secondary valence forces and there is considerable experimental evidence to substantiate its conclusions (8,21).

After tracing the historical growth of resinous adhesives, we shall cover briefly specific applications of resin-bonded plywood. Largely because of its importance in relation to National Defense, we shall cover rather carefully the use of phenolic resin adhesives in the manufacture and production of aircraft.

HISTORICAL BACKGROUND

Before proceeding with the discussion of the development of synthetic resins for plywood, it might be well to discuss the nature of plywood and to compare it with solid wood. Wood has been used by man for many centuries. It is plentiful, cheap and easily worked to produce useful articles. It has excellent mechanical properties, is light in weight and certain types, because of inherent beauty of figure and texture, find use in decorative application. Together with these advantages, wood does have certain definite limitations. It is ununiform, swells on absorbing moisture, shrinks on losing it, warps badly, is flammable, and its strength characteristics vary enormously with and against the grain. There is evidence that as early as 2000 years ago, the Chinese made the first veneered woods in an effort to overcome some of these limitations. Undoubtedly, they were primarily interested in decorative effect rather than mechanical properties. Probably plywood, as it is known today, first came into general use about 1870 (18). This development was a natural outgrowth of the attempts to use wood to greatest advantage. It was found that many of the defects of solid wood could be overcome by cutting into relatively thin sheets (generally called veneers), cross-layering the veneers and glueing them together. These veneers generally vary in thickness from about 1/32" to 1/4", although veneers as thin as 1/100" or less are often cut for special purposes. In general, it has been found that best results are obtained from the so-called "balanced construction", that is the cross layering of an odd number of plies, such as 3,5,7, etc. Many of the common types of wood are widely used in the manufacture of plywood, although certain species can be used to greater advantage than others.

A. Mora, in his book on plywood (19), listed the following characteristics in which plywood is superior to lumber:

1-Plywood is slightly heavier and harder.

2-Plywood shows less volume change and warping with variations in humidity.

3-Tensile, compressive and impact strength are more uniform than in lumber.

4-Plywood shows less splitting.

5-Weight for weight, plywood is stronger.

In the development of plywood, it soon became evident that the limiting factor was the glue line. In the early days, the adhesive was generally an animal or fish glue. Later these were to a large extent replaced by the cheaper "vegetable" glues made chiefly from tapioca starch. All these adhesives suffered from serious drawbacks. Because of the large quantities of water used in the preparation of the adhesive, careful control was necessary to prevent warping and swelling. Moreover, the process was slow and laborious due to the necessity of conditioning the plywood after its preparation. But a much more serious drawback was the poor resistance of the glue line to water and mold growth. Definite improvements in water resistance resulted from the introduction of casein and glues made from blood albumen which came later. However, only with the introduction of synthetic resins was it found possible to obtain a glue line which could be truly called water-proof and mold-proof.

Probably the first record of an attempt to use phenolic resins in the manufacture of plywood is given in a British patent which issued in 1901. (3). Presumably the possible uses of their resins in this field was very much in the mind of Baekeland and his co-workers in the years between 1900 and 1910. In 1910, a French patent (11) issued covering the use of a phenolic resin film in the manufacture of plywood. In 1918 a patent was granted to McClain (30), covering the use of a phenolic resin in film form, but there is no evidence that this process was ever very widely used. It seems clear, therefore that in the period from 1901 through the first World War, nothing of commercial importance appears to have taken place. The best evidence that resin-bonded plywood was a rarity in this period is that plywood made for aircraft during the war was glued with casein and blood. This fact in itself later proved to be a serious obstacle to the subsequent development of plywood, because of the delamination of large quantities of surplus military plywood stored for several years after the completion of the war.

In the latter part of the decade between 1920 and 1930, there was very active development work in the field. There seems to be little question that the products investigated initially were solutions or dispersions of phenolic resins. One company marketed for some time a dispersion of a phenolic resin in water. This process never became a great success chiefly because of the difficulty of controlling spread and adjusting moisture content at the time of gluing. Attempts were made to use phenolic resins in alcoholic solutions, the form in which they were most generally available. However, there was some hazard resulting from the presence of the somewhat flammable alcohol and here again the difficulties of uniform spread and proper control of flow proved difficult hurdles to surmount. Considerable work was also carried out with a phenolic resin applied to the veneer in the form of a powder (31). In order to obtain adequate flow, it was necessary to add water after coating the veneers, thus introducing an added operation. The equipment and care required to operate this process proved insurmountable obstacles and this process fell by the wayside. While work of this nature was going on in this country, in Europe there was very active development on the production of a phenolic resin in film form (32,33). In 1932, a symposium was held at a meeting of the American Society of Mechanical Engineers at Jamestown, N. Y. in which the four available resin forms were discussed (28). At that time, it was too early to predict which type would prove to be the most generally useful, although experience in Europe already pointed toward the advantages of the film. In the following year, Sorensen presented an excellent paper before the American Society of Mechanical Engineers (25), describing more fully the resin film which was at that time manufactured in Europe. In 1934, manufacture was begun in this country and from that time on the growth of resin-bonded plywood advanced rapidly.

At this point it might be well to describe briefly the nature of this resin film, the reason for its success, and the method of preparing plywood from it. The adoption of resin film by the plywood manufacturer was the result of several advantages. First, a uniform spread is assured, thus permitting uniform bonding. Second, it is a dry process and there is, therefore, no swelling which results from the introduction of water. Third, the process is rapid, simple and clean. Fourth, light colored, thin veneers can be used without danger of staining. Fifth, the bond is absolutely moldproof and water-proof, being resistant even to boiling water.

In the preparation of the film phenol and formaldehyde are first reacted in molecular proportions in the presence of a small amount of sodium hydroxide as a catalyst. The resulting product, without being carried to the point of water separation, is impregnated on a tissue paper carrier and subsequently dried. In commercial practice the paper is .001" thick and the resultant film is slightly over .002" thick. The film as supplied today contains approximately two parts of resin to one part of paper (27). With the development of satisfactory equipment, it has become possible to produce this film commercially in widths of 74" or more at a cost to permit its utilization even where economy is an important factor. The film has excellent stability and under normal conditions may be kept for approximately a year before use. Cresol may be substituted wholly or in part for the phenol. The differences produced are slight, cresol resins giving slightly slower cure, a slight odor, and the shear value is somewhat lower.

In the process of manufacturing plywood, using resin film the film is first cut to size, and then slipped between veneers held at a moisture content of approximately 8% to 10% (25). The assembly is then loaded into the hot press - mechanical loading devices are often used - pressure is applied for a few minutes and the panels are removed from the hot press and allowed to cool, or in some cases dipped in water. The panel is now ready for trimming and sanding and other operations without any further delay. The temperatures generally used are in the range of 275°-300°F. The time in the press may vary from five minutes to twenty minutes, depending on the thickness of the panel. Normal pressures vary from 125 to 250 lb. per sq. in., depending on the type of wood, higher pressures being used for the harder, denser woods, and lower pressures for the softer, more absorbent woods. The method of manufacturing plywood using the resin film is a simple one, although it requires careful control of four variables, viz. (1) moisture content of the veneer, (2) temperature, (3) pressure, and (4) time.

The year 1934 witnessed the beginning of the rapid growth of resin bonded plywood. For the period of 1934 through 1937, the resin film was practically the sole type of resinous adhesive used. One important exception, was the Douglas Fir plywood industry. Here it was never possible to work out application conditions for the film to meet the demands of this mass production industry. Moreover, largely because of rough veneer cutting and ununiform density of the species, it was found that the film itself did not appear to be entirely suitable for this type of wood. In this field, therefore, during the period discussed, there were only one or two important manufacturers producing resin-bonded plywood and they used the more conventional alcohol soluble phenol-formaldehyde resin.

As the number of hot presses in the plywood plants grew, it was only natural that thought should be given to the question of producing a cheaper and more economical plywood. It was realized that for many applications, the absolute boil-proofness and high shear value of the resin film was not needed. For exterior panels, aircraft, 2-ply faces, and other applications where maximum durability or special characteristics were required, the resin film held its own. However, there were a number of uses where maximum durability was not essential and for such applications aqueous urea-formaldehyde resins proved very satisfactory. In the year 1937, urea-formaldehyde resins were successfully used for the first time on a commercial scale. Resins of this type had important advantages. They were cheap, could be mixed with flour and other inert extenders, and they could be used at temperatures around 230°F. as compared to 285°-300°F. for the phenolic film. By the year 1939, it is believed that the use of urea-formaldehyde resins had grown to the point where the quantity of plywood manufactured had already equalled that made from phenolic resin. However, as this paper is limited to phenolic resins, this important development will not be discussed further.

While these important developments were taking place in the field of urea-formaldehyde resins, intense activity was in progress in the phenolic resins. On the Pacific Coast, where the production of Douglas Fir plywood was growing by leaps and bounds, it was realized that improvements in the alcoholic type resin were vitally necessary. If shipped and stored in the alcoholic solution, its storage characteristics were poor. If shipped in lump form for dissolving in alcohol at the plywood plant, the operation was messy and cumbersome. Moreover, the use of alcohol is always disadvantageous in a wood-working plant. Of real importance during the year 1940 is the announcement of three new phenolic resins in powder form for use in the manufacture of plywood. All of these resins have certain factors in common. First, they are all supplied in powder form; second, they all dissolve readily in water; third, they all make waterproof, boil-proof bonds comparable in quality with those obtained from the use of resin film. One of the types is intended for use in temperatures about 300°F., and is generally recommended for use without the addition of any extender. The second type is suggested for use with fairly large quantities of blood or other protein matter at temperatures about 240°F., and an excellent bond is obtained particularly with Douglas Fir. The third product is the most interesting of all because it represents an important advance in the synthesis of phenolic resins. For the first time, a product is available which combines numerous advantages. This new resin can be used at temperatures of 230°-250°F.; it is available as a powder of good stability which dissolves readily in water; it is stable over a wide range of pH; the bonds have outstanding mold and water resistance, being resistant to boiling water. More will be said about this resin when we discuss applications in the aircraft field.

Before leaving the field of resin developments, we should say a word about resins intended for use in the cold bonding procedure. This description is perhaps somewhat misleading. When we refer to the cold bonding of plywood, we generally mean that the material was not made by the simultaneous application of heat and pressure. Often the adhesive is applied to the surfaces of the veneer and subsequently put in a kiln at a somewhat elevated temperature. This particular field of application is important in aircraft because in the assembly of a plywood plane it is not possible to apply simultaneously heat and pressure. So far, urea-formaldehyde resins are widely used and despite their poor resistance to boiling water, are very satisfactory and have been approved by the Civil Aeronautics Authority. At least one large aircraft manufacturer is using a phenolic resin presumably catalysed by a strong acid catalyst for this application (13).

RESIN BONDED PLYWOOD IN THE AIRCRAFT FIELD

In consequence of the availability of a superior plywood resulting from the use of synthetic resins, the growth of plywood in fields such as furniture, housing, radios, automobiles, ship-building - pleasure, commercial, and military - and in specialty application field such as trays, sporting goods, etc. has been tremendous. In this paper, however, many of these various applications, interesting as they are, will be disregarded. In the limited space available, the importance of plywood in the problems of National Defense, with special emphasis on aircraft, will be discussed. Perhaps the three most important fields where plywood is directly used are, those of housing, marine and aircraft construction. In the housing field, prefabricated units of plywood are an important application. In the marine field, the torpedo boats about which so much has been written, are constructed from large panels of resin-bonded plywood. As for the aircraft field, it will be discussed somewhat fully.

Before beginning our discussion of the aircraft field, it might be well to mention a product known as "Improved Wood" (4,16,17) which represents a further extension of the idea of applying resins to wood. In the work on plywood already described, the actual penetration of the resin into the plies is in all cases very slight and the weight of resin is only a very small percentage of the total. It was felt that the disadvantages resulting from the fibrous nature of wood might be considerably reduced if the resin content were increased. Investigation of this basic idea resulted in the production of the so-called "Improved Wood". In producing this product, a multiple assembly of thin plies (approximately 1/60" thickness) with sheets of resin film interleaved between the plies, is subjected to a pressure of approximately 400 to 500 lb. per square inch. In some cases, it is more advantageous to use the resin in liquid form. The assembly often contains as many as 40 or 50 plies. It has been found advantageous in some cases to have only every tenth ply cross grained rather than cross graining alternate plies as is the case with the usual plywood. As a result of the penetration of the resin into the wood, the final product has properties far superior not only to wood itself but also to resin-bonded plywood. (Table I). Table I indicates the advantages of "Improved Wood" over resin bonded plywood in the case of both beech and birch. Worth noting particularly is the hugh increase in strength across the grain, the large increase in specific gravity, the reduction in water absorption, and the decrease in swelling.

So far the chief application of the "Improved Wood" is in aircraft construction where it is used in making struts, supporting members, etc. Its chief advantages are freedom from knots and imperfections as well as unity in change of dimensions on exposure to water. Other applications of "Improved Wood" are in the manufacture of masts, radio towers, bridges, truck bodies, marine masts, skis, tennis rackets, hockey sticks and the like.

An excellent paper recently appeared giving important data on the mechanical properties of "Improved Wood" (5).

Turning now to the aircraft field, an attempt will be made to point out the important features so that the main applications may be observed and important trends indicated. We might say that phenolic resins enter into the construction of the modern plywood plane in four different ways; one, as a flat sheet which is subsequently formed and shaped; two, as high density plywood (Improved Wood); three, in the so-called "Plastic" plane; and four, as the cold bonding adhesive used in assembly work. Advantages resulting from the use of plywood are as follows: (1)-speed of production, (2)-high stiffness per unit of weight (approximately 18 times that of Dural), (3)-improved product (better streamlining, etc.), (4)-decreased cost and weight, (5)-reduction in the number of skilled men required for fabrication, and (6) simplification of machinery. Another indirect advantage resulting from the use of plywood is the release of such strategic metals as aluminum and magnesium for other purposes. Disadvantages resulting from the use of plywood are (1) poor flammability characteristics, and (2) poor structural characteristics in certain respects. Plywood finds its chief use in the construction of military trainers. There are still very good reasons for the use of metal in bombers, transports, pursuit and scout planes, although certain sections of the larger planes such as the floor, bomb-bay doors, etc. are being built of plywood.

Referring now to the three general classifications in which plywood is used, the flat sheets are employed in the manufacture of spars, wing coverings, ribs, gussets, floors, doors, etc. In most cases, these sheets are manufactured from resin film. Turning to high density plywood, they find their chief application in the production of reinforcing plates and spars, as well as propellors. The resistance to shear and nail-holding power are very far superior to that of solid wood.

Before leaving our subject, just a word about the so-called "Plastic" plane (7,12,27). The name itself is somewhat misleading. The "Plastic" plane actually contains about 90% of wood veneer and 10% of synthetic resin on a weight basis. Phenol-formaldehyde, urea-formaldehyde, and thermoplastic resins such as the polyvinyl acetals, have been used as the bonding agents. All of these types have some advantages, as well as certain disadvantages, but it would appear that the phenolic resin has already found the widest application and will continue to dominate the field. The "Plastic" plane is one in which the veneers are resin-bonded over a form or die instead of in the usual flat condition so that the resultant plywood is already shaped. "The principles involved in molding plywood are old and the only novel features were the methods of applying the pressure as well as the unusually large size of the molded unit. The fundamental principle involved is that of using an inflated or deflated rubber bag as one of the halves of a pair of molding dies. There is not only a saving in matching up the dies where the intermediate distance between the halves must be very accurately determined, but in many cases the dies are wholly eliminated and, in any event, the rubber bag pressure is of the order of fluid pressure and at substantially right angles to any surface that is under pressure." (24). There are a number of different processes, the three best known being the Duramold, Vidal and Timm. Although much has been written about these processes, many of the actual details still remain secret. There are obvious advantages in the "Plastic" plane. It presents smooth exteriors, thus exerting less aerodynamic drag, it can be made rapidly and inexpensively. As illustrative of the number of mechanical problems, there are a series of approximately thirty patents describing variations in fuselage construction.

Comparing the advantages and disadvantages of the three general types of adhesives indicated above, the following factors warrant consideration. First of all, temperature is extremely important because the life of the rubber bag, whether it be natural or synthetic, depends chiefly on the temperature to which it is subjected. In this characteristic the urea-formaldehyde and thermoplastic resins have a definite advantage compared to the conventional phenol-formaldehyde resin of the past because they can be used at lower temperatures. However, both of these resins have serious disadvantages. There is a serious question concerning the durability of plywood bonded with urea-formaldehyde resins when subjected to extreme weather conditions. The use of a thermoplastic resin raises serious questions regarding the behavior of the product under conditions of extreme heat. With the development of low temperature phenol-formaldehyde resin in powder form described earlier in this paper, it would seem that the one serious disadvantage of the phenolic resin has been overcome, namely the necessity of operating at a high temperature. It is anticipated that as time goes on, the "Plastic" plane will increase in importance. The mechanical difficulties of operation can undoubtedly be overcome and it seems that we are well on the road to having a satisfactory and ideal adhesive.

Our discussion of the plywood plane would be incomplete without discussing the methods of assembling the various resin-bonded structures. In the past the adhesives have been casein and animal glue. Obviously it would not make very good sense to build a plane of resin-bonded plywood without having the joints equally well bonded. For this purpose, a urea-formaldehyde resin is generally used with an acid catalyst. The durability characteristics in this type of application seem ample for the conditions of service. An interesting development in the field of equipment has been that of high frequency electrostatic heating devices (6). Although this type of equipment has not to the best of our knowledge been applied to the production of assembly bonds, the use in this field is obviously indicated as it would permit the application of heat and pressure to thick assemblies and irregular shapes and forms.

SUMMARY

Despite the more impressive applications of phenolic resins in the field of molding and coatings, it can be seen that they play an important part in the manufacture of plywood. The importance of such plywood has grown tremendously in the last few years and is of great importance at the present time in our program of National Defense. There seems little doubt that the importance of plywood in aircraft construction is just beginning to be appreciated in an industry which has heretofore devoted its attention almost exclusively to metals.

With the availability of a fast curing, easily handled powdered phenolic resin to supplement the phenolic resin film, the major adhesive problems seem already well on the way to solution.

END

"Phenolic Resins for Plywood" - L. Klein. (A.C.S. Meeting April 1941)

TABLE I

Property	Grain Direction of Sample	Beech			Birch		
		Resin-bonded Plywood	"Improved Wood" 45 ply	Increase %	Resin-bonded Plywood	"Improved Wood" 50 ply	Increase %
Specific Gravity		0.65	0.94	+45	0.67	1.00	+49
Water Content (%)		9.0	6.0	-35	10.0	6.5	-35
Tensile Strength	with against	1400 100	1290 215	-7.9 +1.5	1380 75	1280 383	-7.3 +410
Compressive Strength	with against	600 -	1350 540	+125 -	700 90	1150 540	+64 +500
Bending Strength	with against	1300 120	2200 360	+69 +200	1400 100	2200 550	+57 +450
Torsion	with against	200 110	320 200	+60 +82	200 -	- -	- -
Modulus of Elasticity	with against	150000 9000	185000 34000	+23 +278	160000 5800	215000 48000	+34 +728
Modulus of Rupture	with	9200	15000	+63	8000	-	-
Water absorption after 50 hrs. immersion (%)		38.5	8.8	-77	43.3	8.0	-82
Swelling after 50 hrs. water immersion (%)	Thickness Width	5.8 3.5	1.05 -	-82 -	5.18 6.5	1.85 0.18	-64 -97

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Compressive Strength	with against	600 -	1350 540	+125 -	700 90	1150 540	+64 +500
Bending Strength	with against	1300 120	2200 360	+69 +200	1400 100	2200 550	+57 +450
Torsion	with against	200 110	320 200	+60 +82	200 -	- -	- -
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BIBLIOGRAPHY

("Phenolic Resins For Plywood" - L. Klein. A.C.S. Meeting April, 1941)

1-Anon, Modern Plastics Catalog, 414 (1941).

2-Anon, Modern Plastics, 17, 25 (1940).

3-British Patent, 17, 327 (1901).

4-Brenner, P., Aircraft Engineering, p. 129 (1938).

5-Bernhard, R. K., Perry T. D., and Stern, E. G., Mechanical Engineering, March 1940.

6-Berkness, I. R., Canadian Wood Worker & Manufacturer 40, 9 (1940).

7-Clark, V. E., Aero Digest, July 1939.

8-DeBruyne, N. A., Aircraft Engineer, Vol. 18, December 28, 1939, p. 51.

9-Decat, R., Aero Digest, 38, 140 (1941).

10-Ellis, G., Chemistry of Synthetic Resins, Vol. 1 Chap. 19, p. 291, Reinhold Publishing Co., N. Y. C.

11-French Patent 414,045 (1910).

12-Hayward, C. H., Wood, 1, p. 443 (1939).

13-Haut, H. N., Chemical Industries, 48, 25 (1941).

14-Koch, R., Modern Plastics, 16, 264 (1938).

15-Koch, R., Modern Plastics, 17, 416 (1939).

16-Kollmann, F., Technology of Wood, Julius Springer, Berlin (1936).

17-Kuech, W., Jahrbuch der Deutsche Luftfahr Forschung (1938).

18-Knight, E. V. and Walpi, M., Veneers & Plywood, Ronald Press, N. Y. C. (1927).

19-Laucks, I. F., Modern Plastics, 15, 294 (1937).

20-Megson, N. J. L., Transactions of Faraday Society, Phenomena of Condensation & Polymerization p. 336, Gurney & Jackson, London.

21-McBain and Lee, W. B., J. Soc. Chem. Ind. Vol. 49 (1927).

22-Moon, H. P., Aviation, 40, 44 (1941).

23-Mora, A., Plywood, Its Production, Use and Properties, Timber & Plywood London (1932).

24-Perry, T. D., Journal of the Aeronautical Sciences 8, 204 (1941).

25-Perry, T. D. and Bretyl, M. F., Trans. A.S.M.E., 60 p. 59 (1938) p. 682 (1938).

26-Spencer, H. S., Modern Plastics, 14, 296 (1936).

27-Sorensen, R. and Klein, L., Hardwood Record, October 1934.

28-Symposium on Glues for Wood Products Trans. A.S.M.E., 54, 1 (1932).

29-Sorensen, R., Trans. A.S.M.E., 56, 37 (1934).

30-U. S. Patent 1,299,747.

31-U. S. Patent 1,922,668.

32-U. S. Patent 1,960,176.

33-U. S. Patent 1,960,177.

END